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SIMULATOR STUDIES OF THE MANUAL CONTROL OF VEHICLE ATTITUDE USING AN ON-OFF REACTION CONTROL SYSTEM

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SUMMARY

A fixed-cockpit simulator and a moving-cockpit simulator have been used to study an on-off reaction control system for manually stabilizing the attitude of a vehicle in the absence of aerodynamic forces.

The data show that the consumption of fuel for reaction control is highly dependent on controller configuration. At the maximum control power tested, an order of magnitude less fuel was used with the three-axis finger-tip controller than with the two-axis pencil controller with toe pedals.

Within the acceleration levels of this investigation, there was no perceptible motion stimulus.

INTRODUCTION

One important problem associated with flight of manned vehicles in the region where the aerodynamic forces become negligible is the control of attitude. During flights above the earth's atmosphere two general types of control systems are suitable: (1) momentum exchange systems which employ inertia wheels or gyros, and (2) jet reaction control systems. Momentum exchange devices are applicable for long durations, while reaction control systems are useful for short duration flights or for short periods of time during longer duration flights. On-off reaction control systems are simple and reliable, thus attractive for use on space vehicles.

In studies, such as that reported in reference 1, an on-off type reaction control system was used, both with a fixed-cockpit simulator in which an analog computer solved the equations of motion, and with a moving-cockpit simulator in which the pilot experienced the motions associated with attitude changes. The study reported in reference 1 primarily investigated the effects on fuel consumption of control configuration (i.e., proportional, on-off, control effectiveness levels and control effectiveness ratio between axes).

The purpose of the study reported herein is to present results of a manual attitude stabilization task, showing the effects on fuel consumption of controller configuration, control power, and motion stimulus when an on-off reaction control system was used.

The major portion of the investigation was conducted on a fixed-base simulator, with an analog computer to solve the vehicle equations of motion and to generate pilot display signals. In a selected portion of the investigation a space-vehicle attitude-motion simulator, supported on an air bearing, was used to determine the effect of motion cues on the ability of the pilot to stabilize the vehicle.

NOTATION

I_X,I_Y,I_Z — moments of inertia about x,y,z axes, respectively, slug-ft^2

I_{XZ} — product of inertia referred to the x and z axes, slug-ft^2

p — rolling velocity, radians/sec

q — pitching velocity, radians/sec

r — yawing velocity, radians/sec

R — ratio of roll control power to pitch or yaw control power

t — time, sec

x,y,z — body axes of vehicle

$\dot{p},\dot{q},\dot{r}$ — angular accelerations about x,y,z axes, respectively, radians/sec^2 or deg/sec^2

$\dot{p}_\delta,\dot{q}_\delta,\dot{r}_\delta$ — angular accelerations produced by the activation of pilot's controller, radians/sec^2 or deg/sec^2

ϵ — inclination of the principal axis with respect to the body axis, deg

$l_{x,y,z}$ — lever arm for reaction controls

EQUIPMENT

The control studies were conducted on both a fixed-cockpit simulator and a moving-cockpit simulator. Identical pilot's controller and attitude displays were provided on both simulators.

Fixed-Cockpit Simulator

The fixed-cockpit simulator consisted of a pilot seat, pilot's controller, and pilot's display. An analog computer represented the vehicle control system, solved the vehicle equations of motion, and generated the signals for the pilot display.

The vehicle equations of motion were:

$$\dot{p} = \frac{I_y - I_z}{I_x} qr + \frac{I_{xz}}{I_x} (\dot{r} + pq) + \dot{p}_\delta$$

$$\dot{q} = \frac{I_z - I_x}{I_y} pr + \frac{I_{xz}}{I_y} (r^2 - p^2) + \dot{q}_\delta$$

$$\dot{r} = \frac{I_x - I_y}{I_z} pq + \frac{I_{xz}}{I_z} (\dot{p} - qr) + \dot{r}_\delta$$

The following inertia values were used in these equations and are identical to those used in reference 1.

$$I_x = 2{,}300 \text{ slug-ft}^2$$

$$I_y = 13{,}000 \text{ slug-ft}^2$$

$$I_z = 14{,}600 \text{ slug-ft}^2$$

$$I_{xz} = 215 \text{ slug-ft}^2$$

$$\epsilon = -1^\circ$$

$$l_x = l_y = l_z = 14.75 \text{ ft}$$

Attitude-Motion Simulator

The attitude-motion simulator is shown in figure 1. It is a steel trusswork 24 feet long, weighing approximately 4200 pounds. It was supported at the center by a 7-3/4-inch-diameter, air-lubricated, steel sphere, ground and polished with a variation of about 0.0001 inch in diameter. The spherical socket had a hard plastic bearing surface, cast to the exact contour of the sphere. Air was injected through a small hole at the bottom of the bearing to provide lubrication between the sphere and the socket. (The socket and sphere are shown in fig. 2.) The air-bearing support system was checked for self-induced torques and friction torques. The data indicate that the combination of these two forces results in negligible torque from the support system.

The reaction control system operated from compressed air storage bottles on-board the vehicle. The air was piped through pressure regulators to pilot controlled solenoid valves and was ejected through convergent-divergent nozzles to produce the jet reaction forces. The level of control power was adjusted by the pressure regulators.

Vehicle attitude signals were generated by on-board transducers, and all recording and display equipment as well as the power supply was on-board the simulator. The absence of mechanical connections with the ground eliminated one source of external torques to the vehicle.

Before each series of runs, the vehicle simulator was balanced to a reference attitude with the aid of electrically driven traveling weights, and the center of gravity was brought as close as possible to the center of rotation. The tests were conducted with the center of gravity about 0.050 inch below the center of rotation. The pilot wore a restraint suit and was instructed to remain as immobile as possible during the tests to minimize extraneous external torques.

Because the external torques were small, the simulator represented a vehicle with approximately zero static and dynamic stability.

(A sketch of this simulator with the pertinent geometric parameters is presented in fig. 3.)

Pilot Display

The pilot's visual display consisted of a gyro horizon for presentation of pitch and roll attitude and a directional gyro which provided heading information. Figure 4 is a photograph of the instrument panel as mounted on the simulator. Various ratios of attitude angle to displayed attitude angle were investigated. It was found that as long as the limits on attitude were easily distinguishable by the pilot, any appropriate ratio was acceptable. A one-to-one ratio of display to attitude angle, such as that used in a conventional airplane gyro horizon, was found to be sufficiently sensitive to enable the pilot to perform the prescribed task. The data presented in this report were all taken with a one-to-one display ratio.

PILOT CONTROLLERS

Roll and pitch were controlled by the simple side-arm pencil controller shown in figures 5 and 6. Pencil controllers have been previously evaluated in reference 2 for aircraft control and in reference 3 for space vehicle control during re-entry. However, the pencil controller used in this investigation had a higher force gradient but required very little travel (about 1/3 inch) and very little force (about 1/5 lb) to activate the controls. The force and deflection characteristics are presented in figure 7(a).

For control about the yaw axis two controller configurations were evaluated. One system used toe pedals the other a simple rocker arm mounted below the pencil controller. The force and deflection characteristics of the rocker arm are presented in figure 7(a) and the characteristics of the toe pedals are presented in figure 7(b).

PILOTING TASK

The task presented to the pilot was that of stabilizing vehicle attitude within $\pm 2^\circ$ for a period of 2 minutes. At the start of each run a small velocity, about $1/2^\circ$ per sec, was introduced about all three axes simultaneously, thus setting the minimum control fuel which could be expended to perform the task.

TESTS

Since a two-axis pencil controller and toe pedals were used successfully during the re-entry control studies on a centrifuge (ref. 3), it appeared desirable to evaluate the suitability of this configuration for attitude control of a vehicle outside the earth's atmosphere. Initial tests were, therefore, conducted with a modified version of the controller configuration reported in reference 3. The majority of the tests, however, were conducted with the same pencil controller but with a simple hand operated rocker arm for yaw control.

Tests with the fixed-cockpit simulator covered a range of control powers up to 10° per second squared and control power ratio between the roll axis and the pitch and yaw axes up to 8. A limited number of control powers were repeated with the moving-cockpit simulator.

Three pilots took part in this investigation. All were NASA research test pilots with considerable experience in a number of different aircraft and piloted flight simulators. Due to the number of test conditions, it was not possible to have each pilot operate all conditions. The data did overlap sufficiently to assure consistent results. Before recording data, the pilot was allowed a few minutes to familiarize himself with the control task and control power levels. During the tests with the moving-cockpit simulator, the cab was closed so that the pilot received no outside visual cues.

RESULTS

Fixed-Cockpit Simulation

As was mentioned previously the initial tests were conducted on the fixed-cockpit simulator with a toe pedal controller for yaw axis control. The data, however, indicated an unexpectedly large proportion (between 80 and 90 percent) of the total fuel was being consumed about the yaw axis. To improve the characteristics of the toe pedals the breakout force and force gradient were reduced to about one half the value shown in figure 7(b) and the total travel was reduced by a factor of four. These changes resulted in only a minor reduction in fuel consumption since the fuel consumed about the yaw axis was still about 75 percent of the total. The yaw control was therefore removed from the toe pedals and placed at the hand in the form of a simple rocker arm. The result was a large saving in fuel at the higher control powers. This is shown in figures 8(a) and (b) where the total fuel consumed about the yaw axis for a 2-minute run is presented. It can be seen in this figure that at a control power of about 8° or 10° per second squared, moving the yaw control from the feet to the finger tips resulted in about an order of magnitude reduction in fuel consumption.

The problem with the toe pedals appears to be the inability of the pilot to effect small impulses. A typical time history (fig. 9(a)) during a 2-minute run points up the short-period limit cycle about the yaw axis as compared to that about the pitch and roll axes. Although the pilot was attempting to impress very short duration impulses, his minimum impulse was considerably larger with his feet than with his fingers. In figure 9(b) a time history of attitude controlled with the rocker arm shows that the impulses about the yaw axis were smaller, resulting in a longer period limit cycle about the yaw axis. The ability to effect smaller impulses with the hand is indicated in references 4 and 5 where it is recommended that the hand or fingers be used where precision is necessary.

Figure 10 presents a comparison of the data of reference 1 with the data of this investigation. The task, simulated vehicle dynamics, and display for this investigation were basically the same as those of reference 1. The major difference between these two investigations is the controller configuration. In reference 1, the two controllers investigated were basically grip type controllers which required movement of the hand and arm for pitch and roll control. One controller required hand movement for yaw control and the other required only thumb movement. It is felt that the large reduction in fuel was the result of using a controller which was operated with a light touch of the fingertips. This enabled the pilot to impress a very small impulse which was sufficient to reduce his initial velocity without a large overshoot.

The average of all the data taken on the fixed-cockpit simulator with the pencil controller and rocker arm is replotted in figure 11, showing an apparent decrease in thrust impulse associated with increase in control-power ratio. This decrease in fuel consumption is an effect of decreasing control power rather than the increase in the ratio itself. This can be seen in figure 12 where the data presented in figure 11 are plotted against pitch and yaw control rather than roll control power. These data emphasize a significant point; that is, the total fuel used for control about any one axis seems to be a function of the control power about that axis rather than the ratio of control power about any two axes.

Moving-Cockpit Simulation

The cold-gas reaction control system on the moving-cockpit simulator limited the available control power to a rather narrow region. However, the data taken on this simulator agree very well with the data from the fixed-cockpit simulator (see fig. 13).

During the stabilization task of this investigation, the pilots experienced no noticeable motion stimulus. As is pointed out in reference 6, at the acceleration levels used in this investigation the angular acceleration was not perceptible by the pilot.

Pilots' Comments

No numerical ratings are included in these data. With just a small disturbance at the initiation of the run, the pilot could quickly return the vehicle to zero attitude about all three axes without much difficulty. In the absence of any further disturbances, the pilot would establish a long-period limit cycle within $\pm 2^{\circ}$ of the reference attitude on all axes for the rest of the 2-minute run. Within the range of control powers investigated, the pilots commented that there were undesirable characteristics (mainly lack of damping), but the control system was acceptable.

One important comment by the pilots was that in both simulators there was an audible cue when the reaction torque was applied. In the fixed cockpit it was an audible click of the controller switches; in the moving cockpit, it was a loud blast from the nozzles. In both cases the pilot commented that the cues definitely helped them introduce the desired magnitude of control impulse.

CONCLUDING REMARKS

The manual control of vehicle attitude with an on-off reaction control system has been studied in fixed- and moving-cockpit simulators. Although the investigation was confined to a specific control task, stabilization to zero attitude within $\pm 2^{\circ}$, the following observations are believed pertinent to the design of suitable controllers for on-off acceleration-command reaction control systems.

The total thrust impulse needed for attitude stabilization depends to a great extent upon the controller configuration.

It appears that within the scope of this investigation a controller designed specifically to be used by the finger tips, rather than a grip type or one that incorporates foot pedals, would enable the pilot to operate the system in a manner which would conserve fuel.

Throughout the range of control powers used in this investigation the pilot experienced no noticeable motion stimulus while operating the control system on the moving-cockpit simulator.

Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., Sept. 10, 1963

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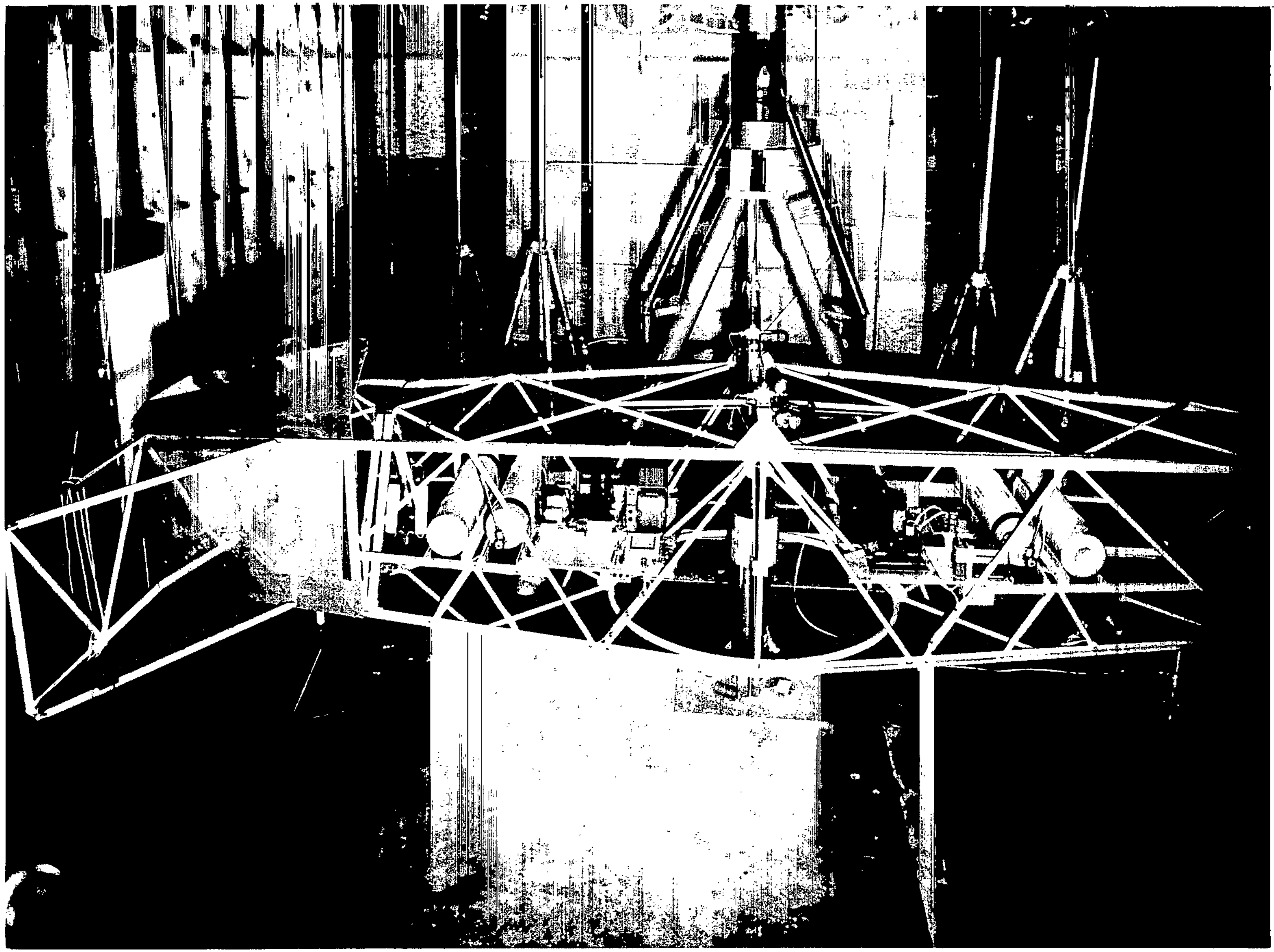

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Figure 1.- Photograph of space-vehicle attitude-motion simulator.

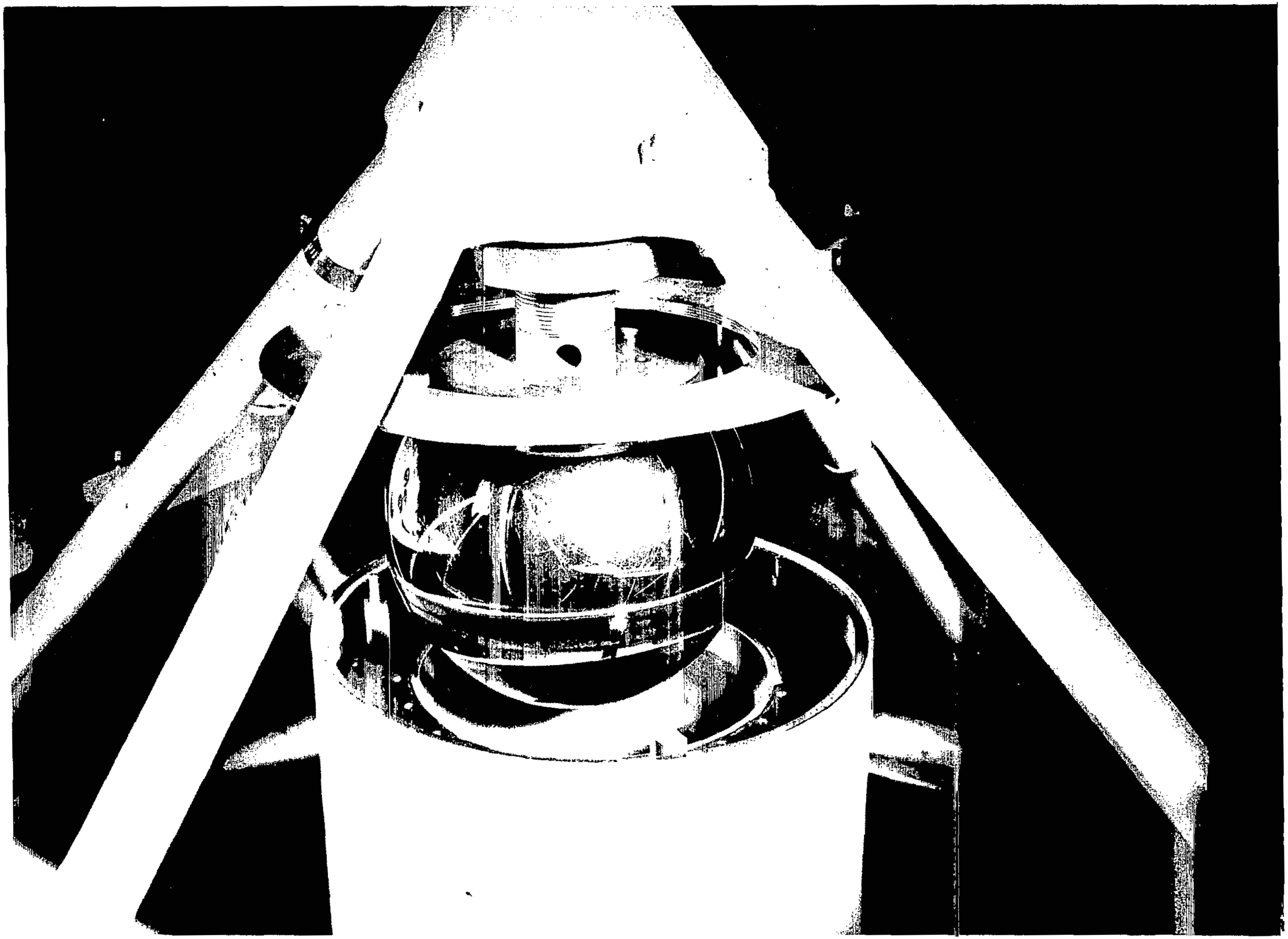

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Figure 2.- Photograph of ball and socket type air bearing.

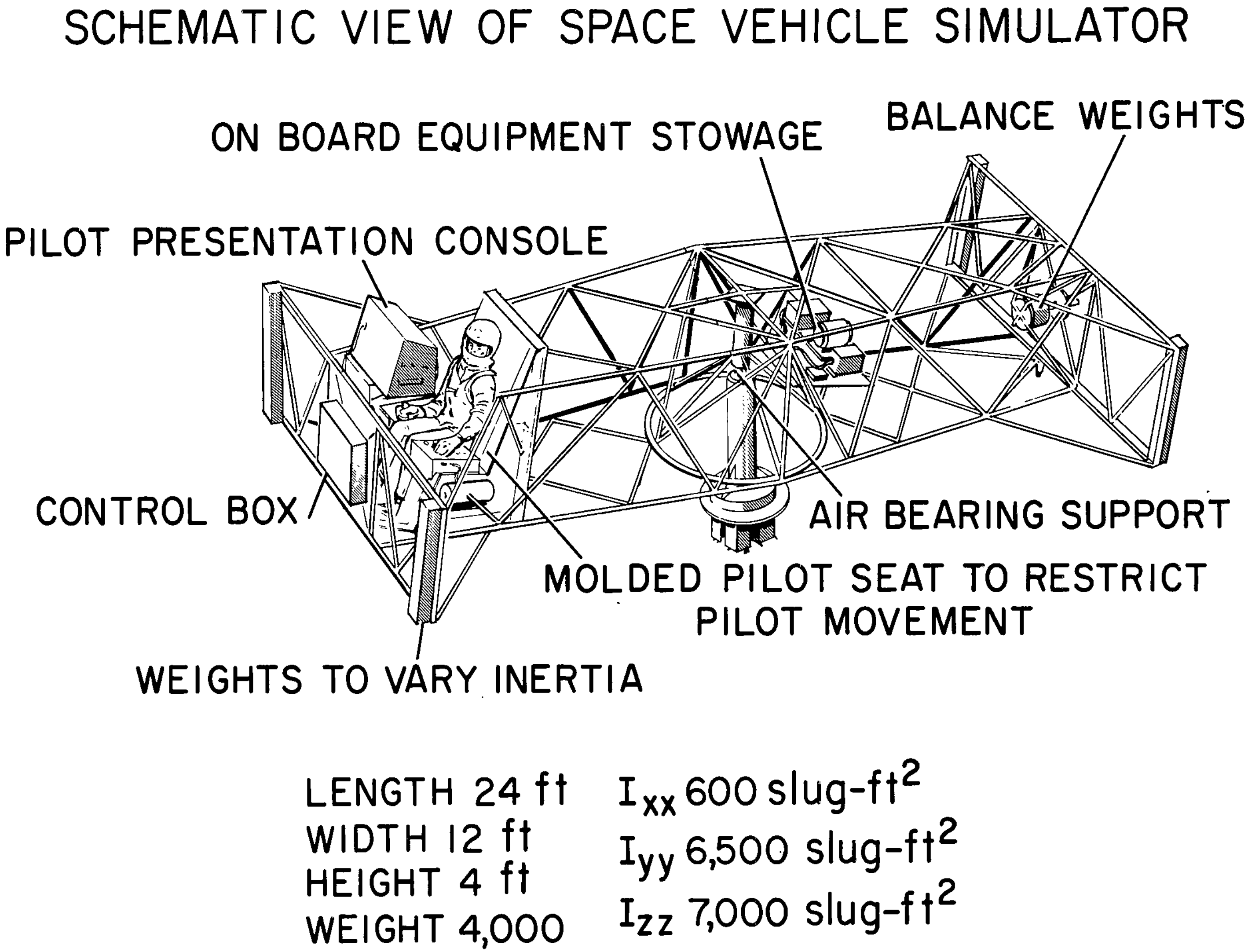

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Figure 3.- Schematic view of space-vehicle attitude-motion simulator.

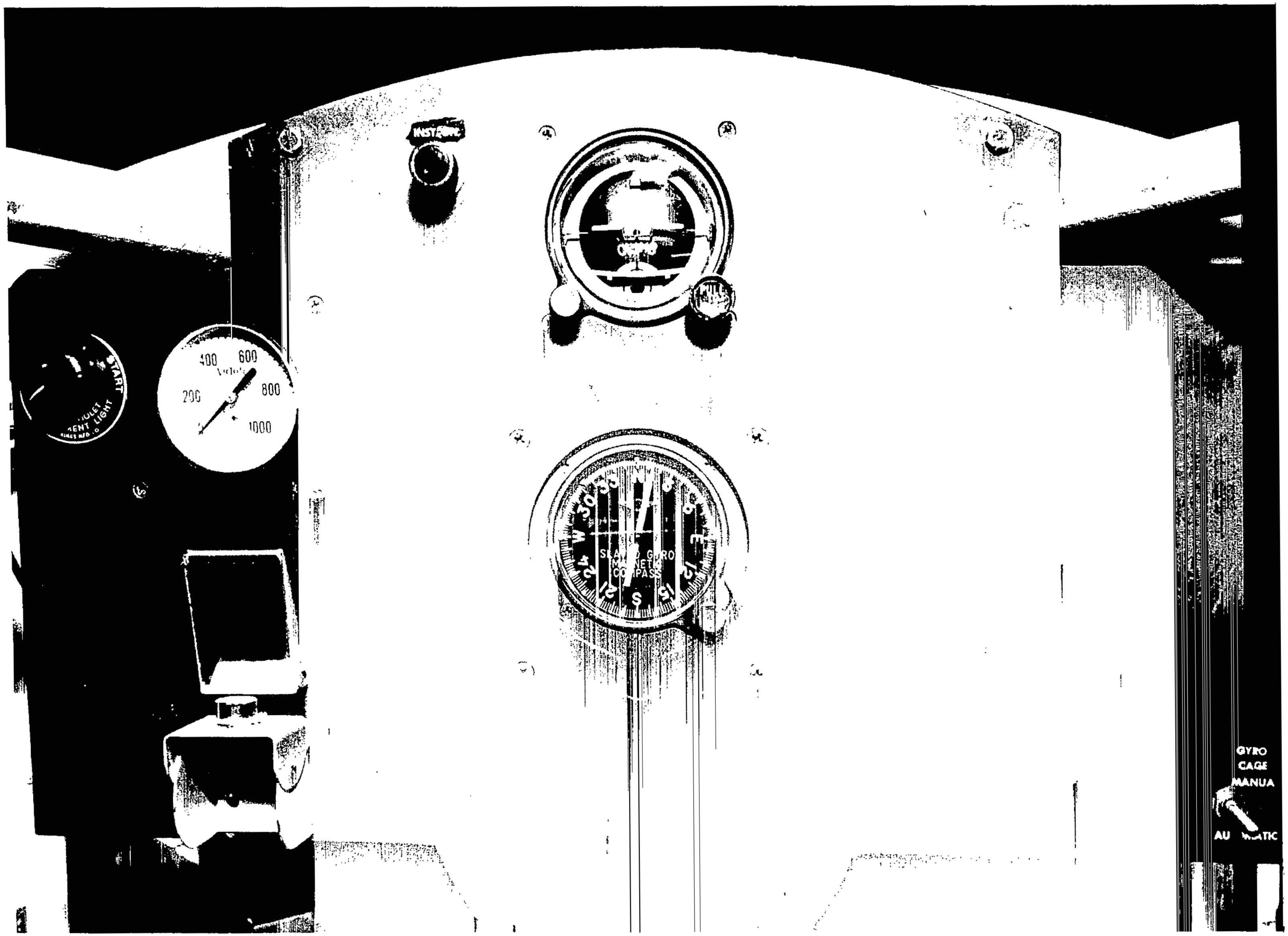

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Figure 4.- Photograph of instrument display panel used in this investigation.

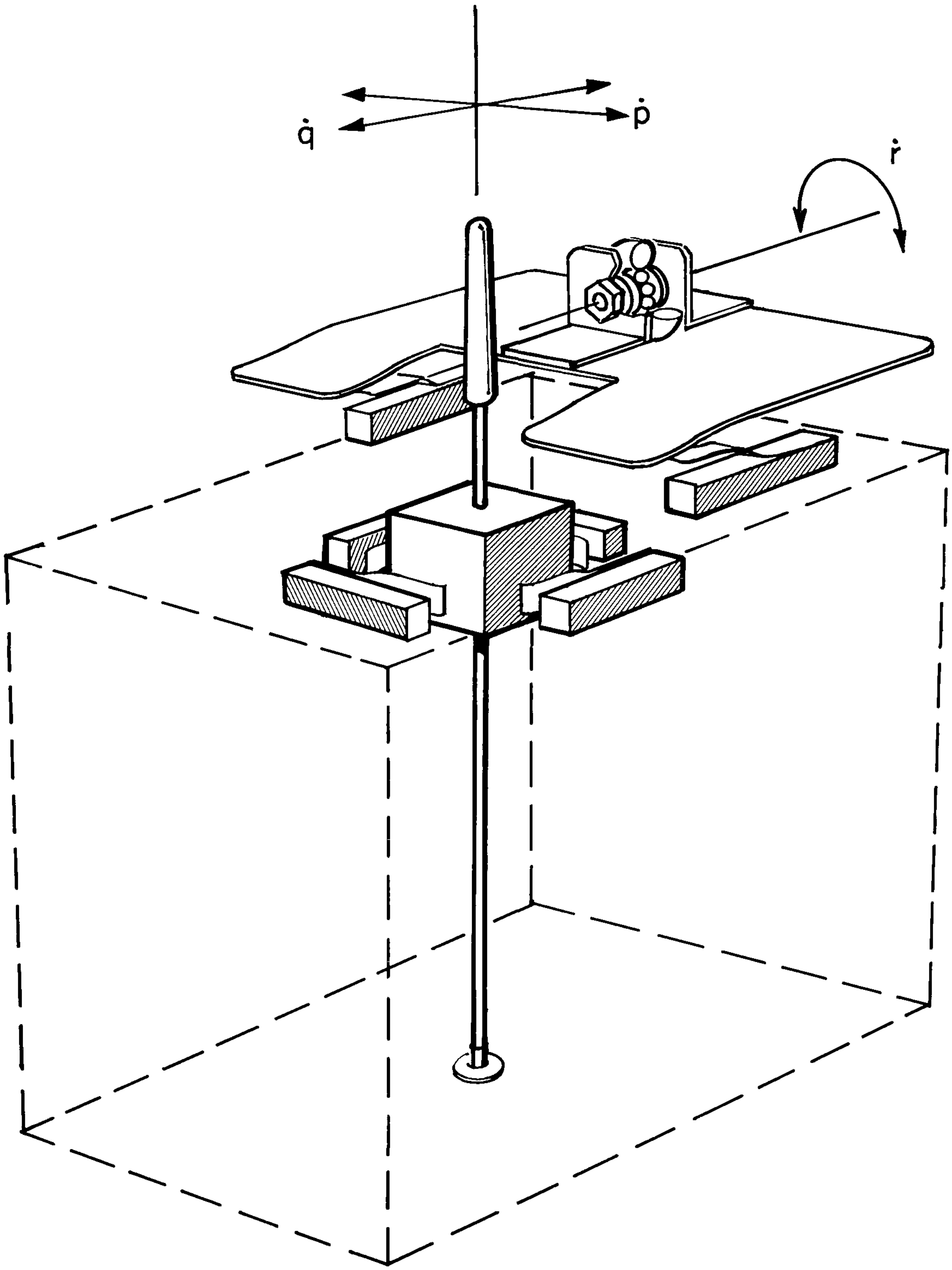

Figure 5.- Schematic view of controller used for on-off reaction control system.

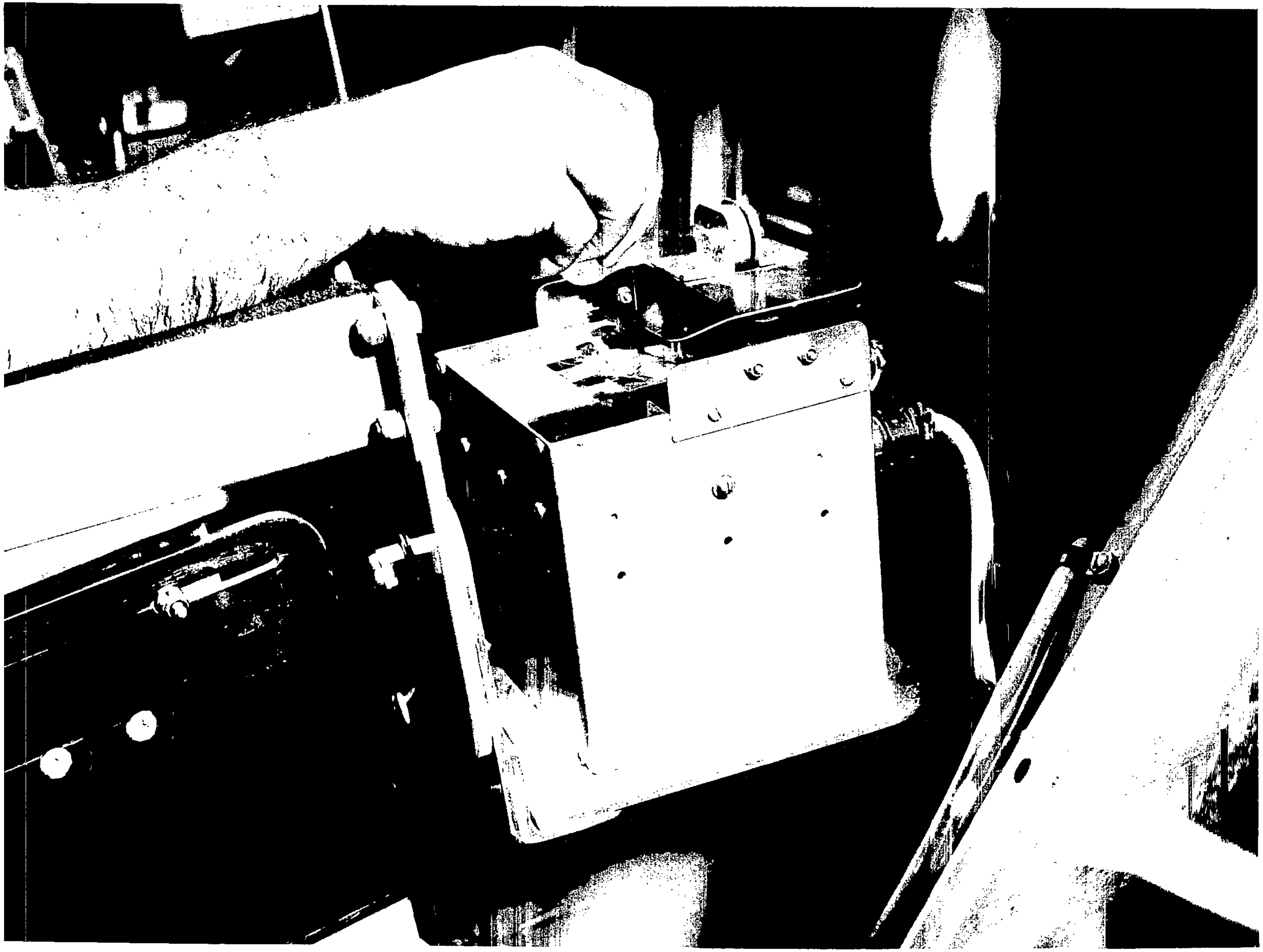

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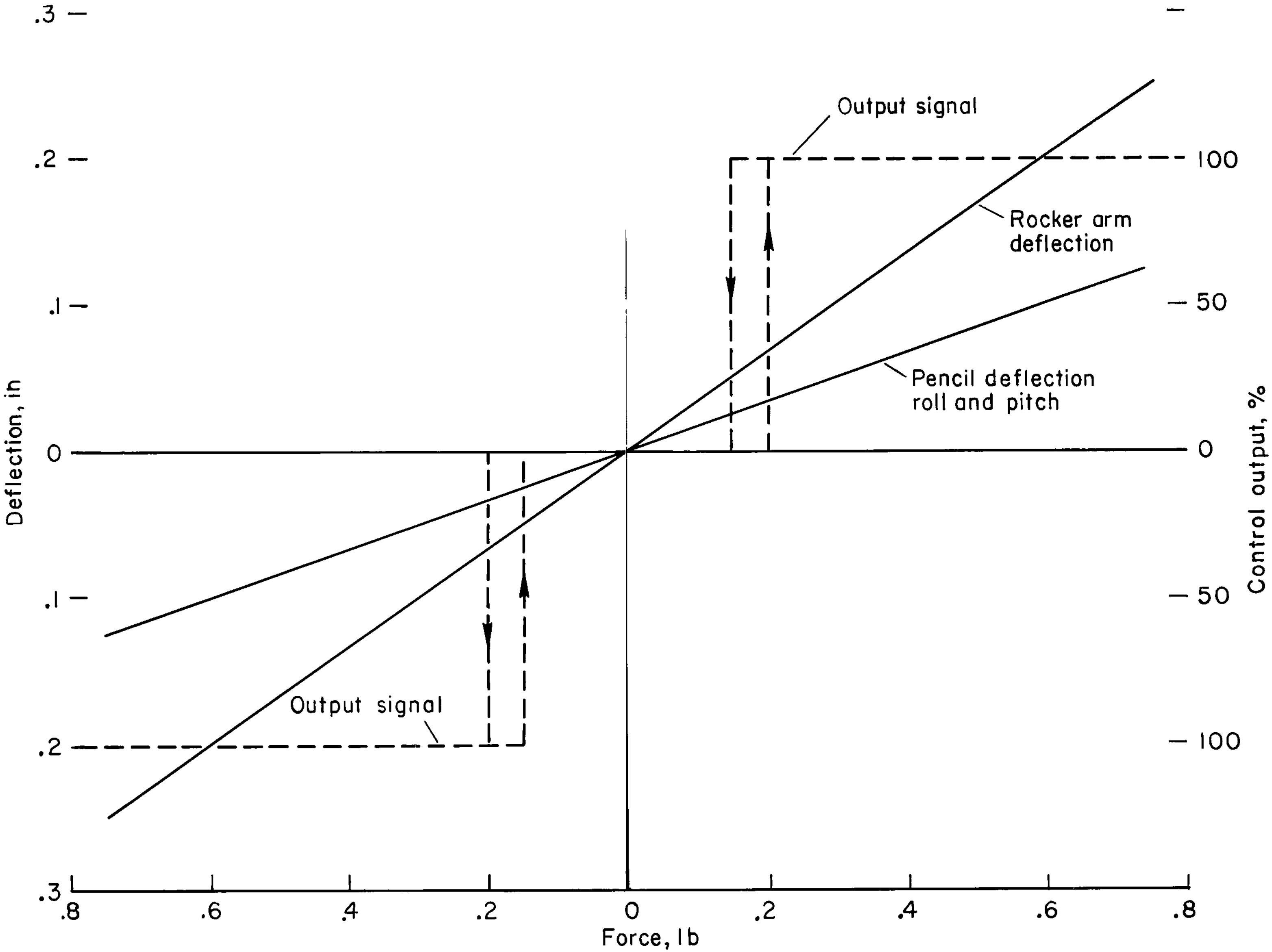
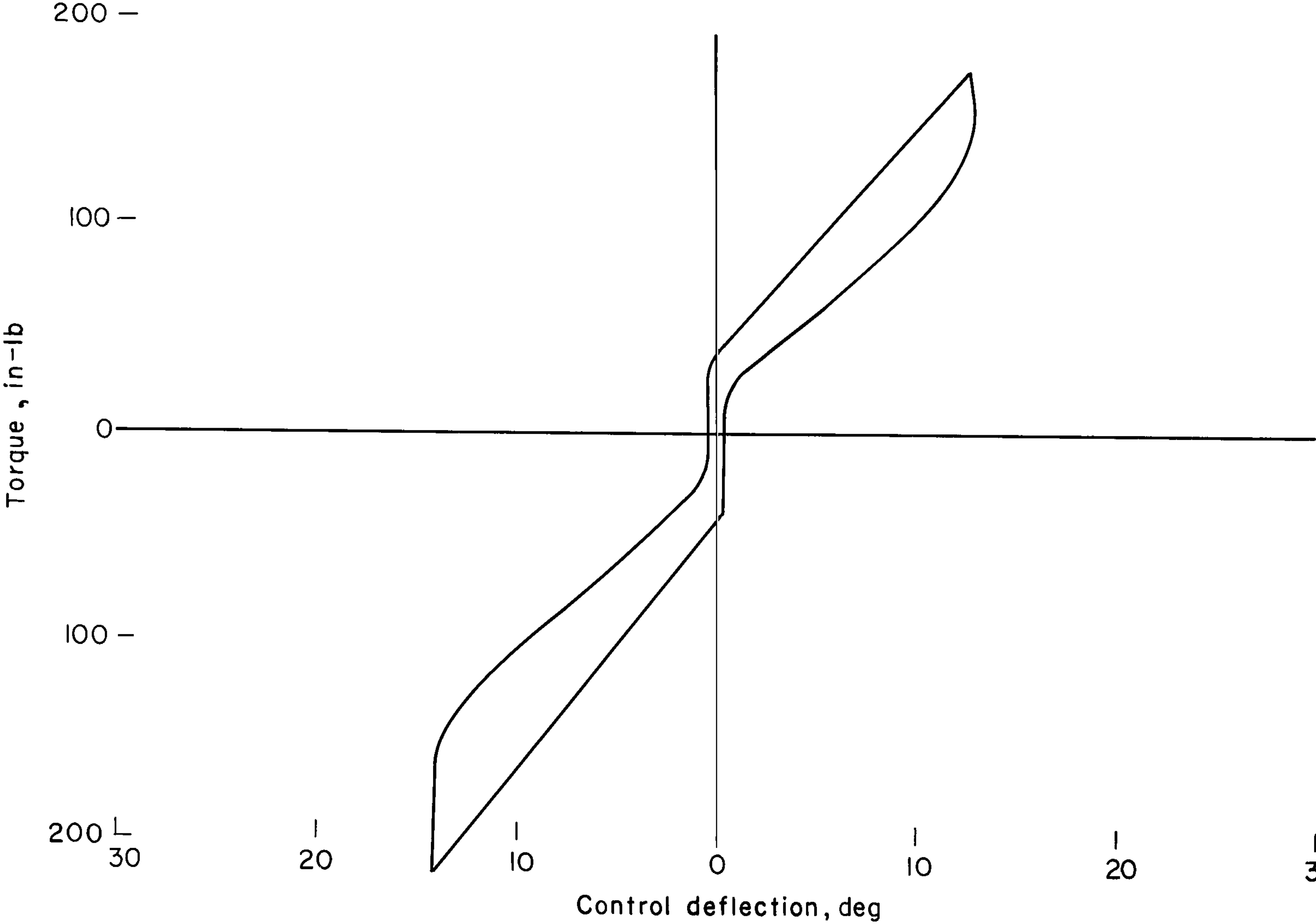
Figure 6.- Photograph of pencil controller with rocker arm mounted in moving-cockpit simulator.



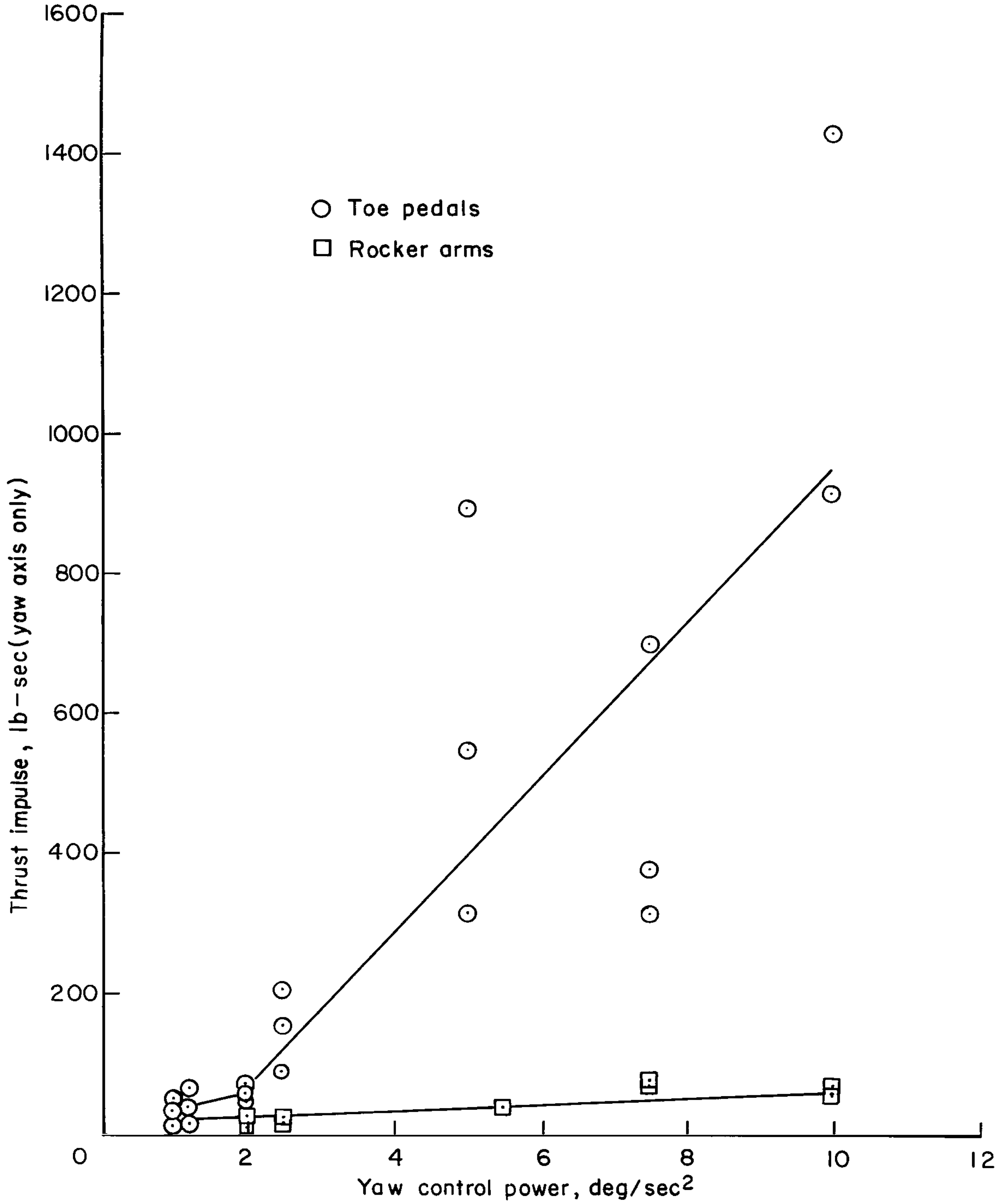
(a) Pencil controller and rocker arm.

Figure 7.- Controller force characteristics.



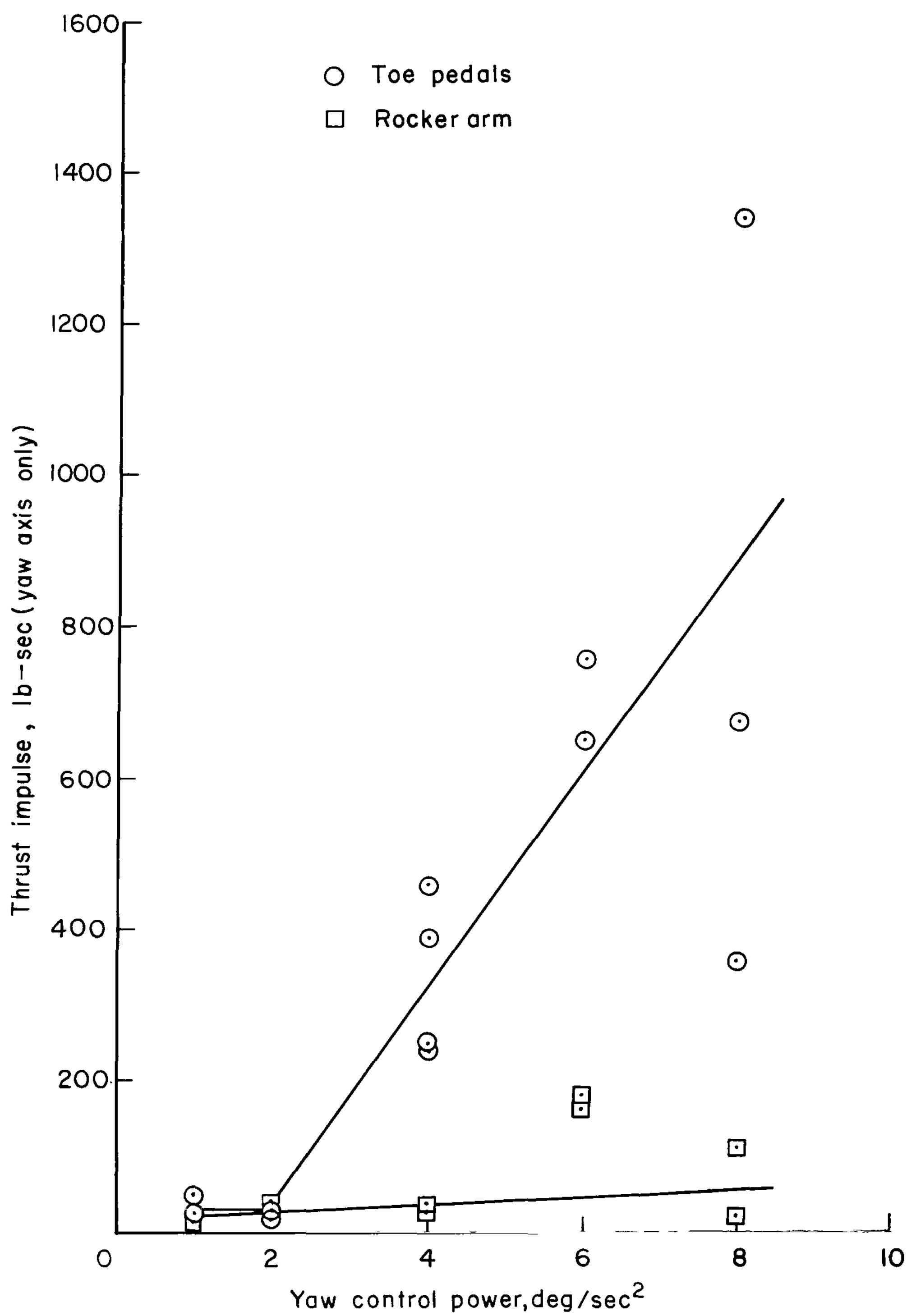
(b) Toe pedals.

Figure 7.- Concluded.



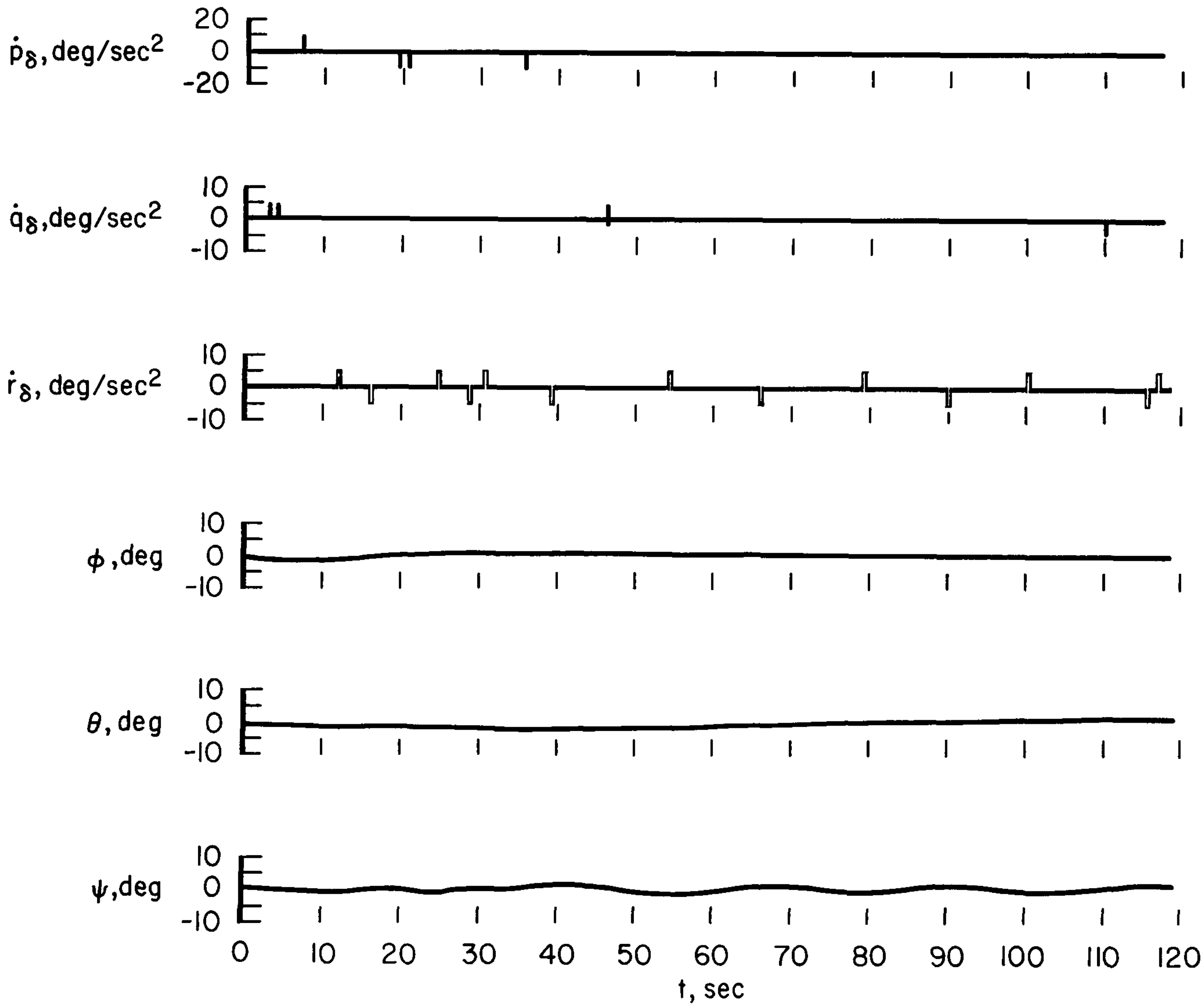
(a) Roll control power, 10°/sec^2.

Figure 8.- Variation of total impulse of the yaw-axis control system with control power.



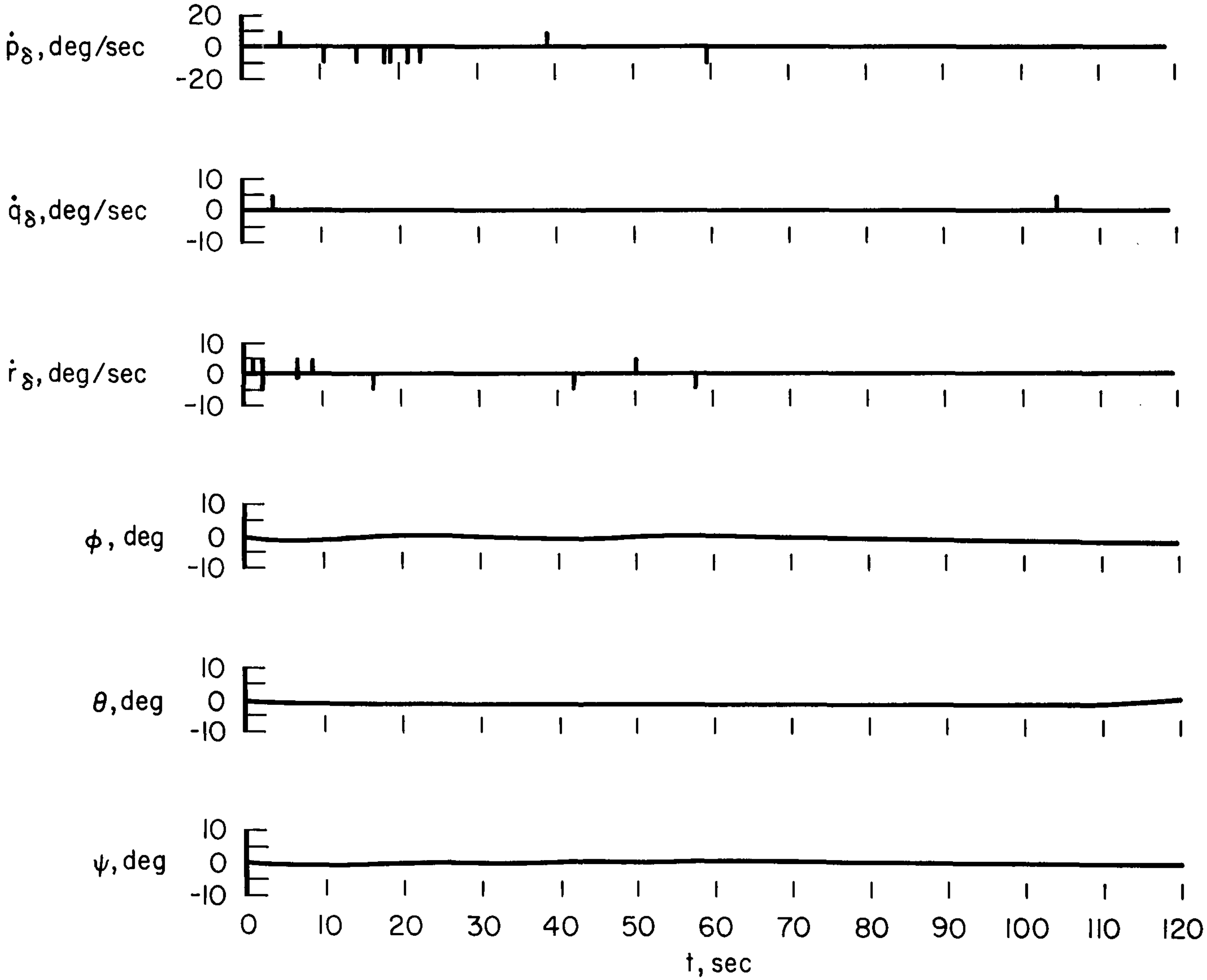
(b) Roll control power, $8^{\circ}/sec^2$.

Figure 8.- Concluded.



(a) Pencil controller with toe pedals.

Figure 9.- Time history of acceleration and attitude; fixed-cockpit simulation.



(b) Pencil controller with rocker arm.

Figure 9.- Concluded.

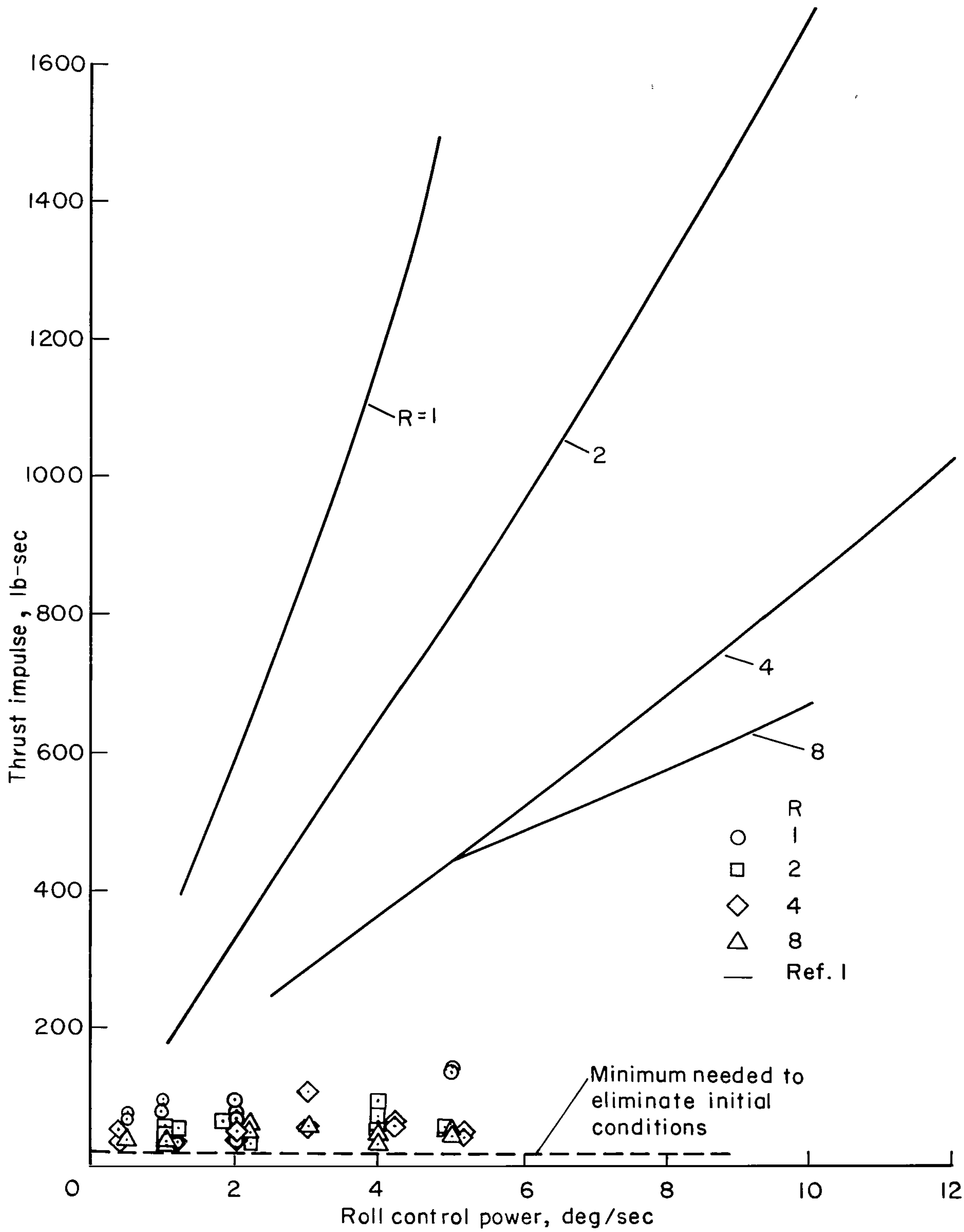


Figure 10.- Variation of total impulse with roll control power; pencil controller and rocker arm.

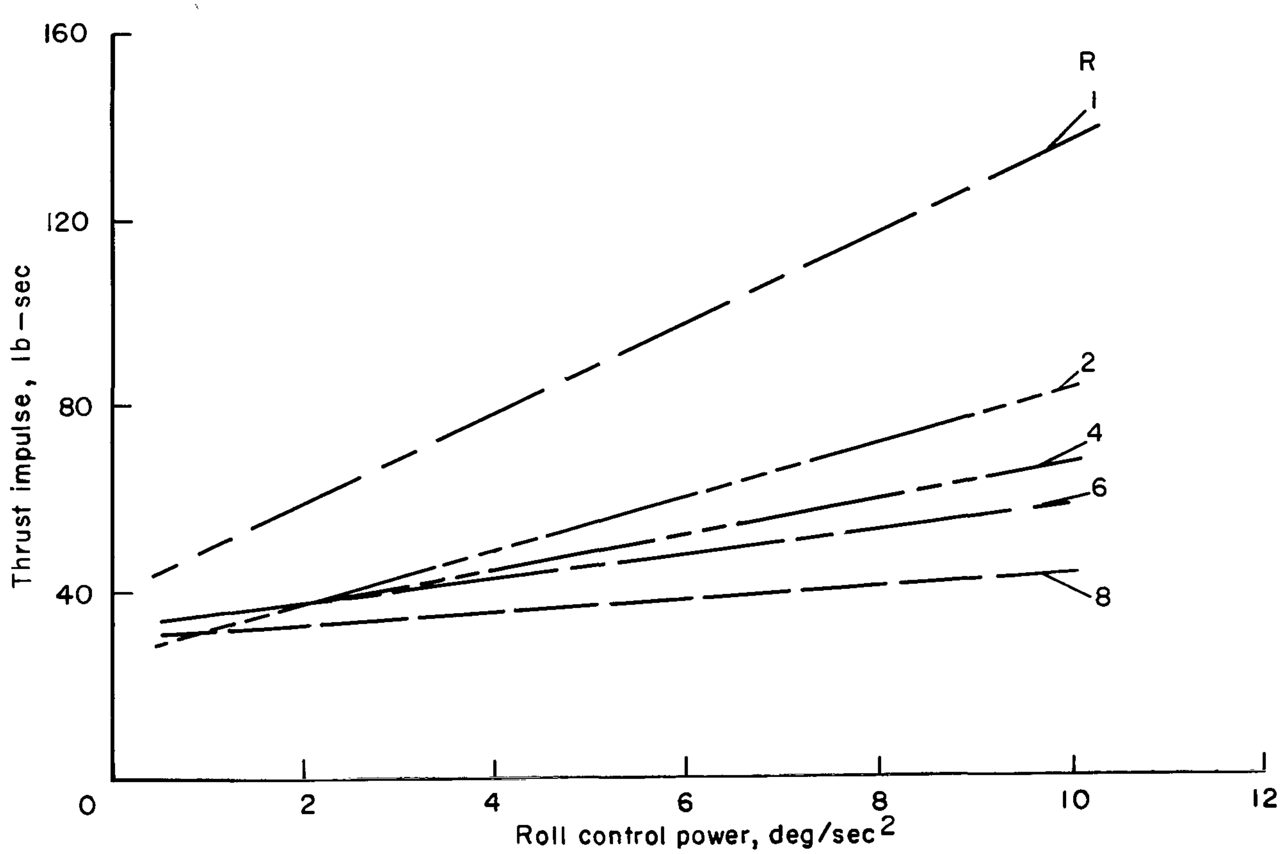


Figure 11.- Variation of total impulse with roll control power for all values of control power ratio investigated.

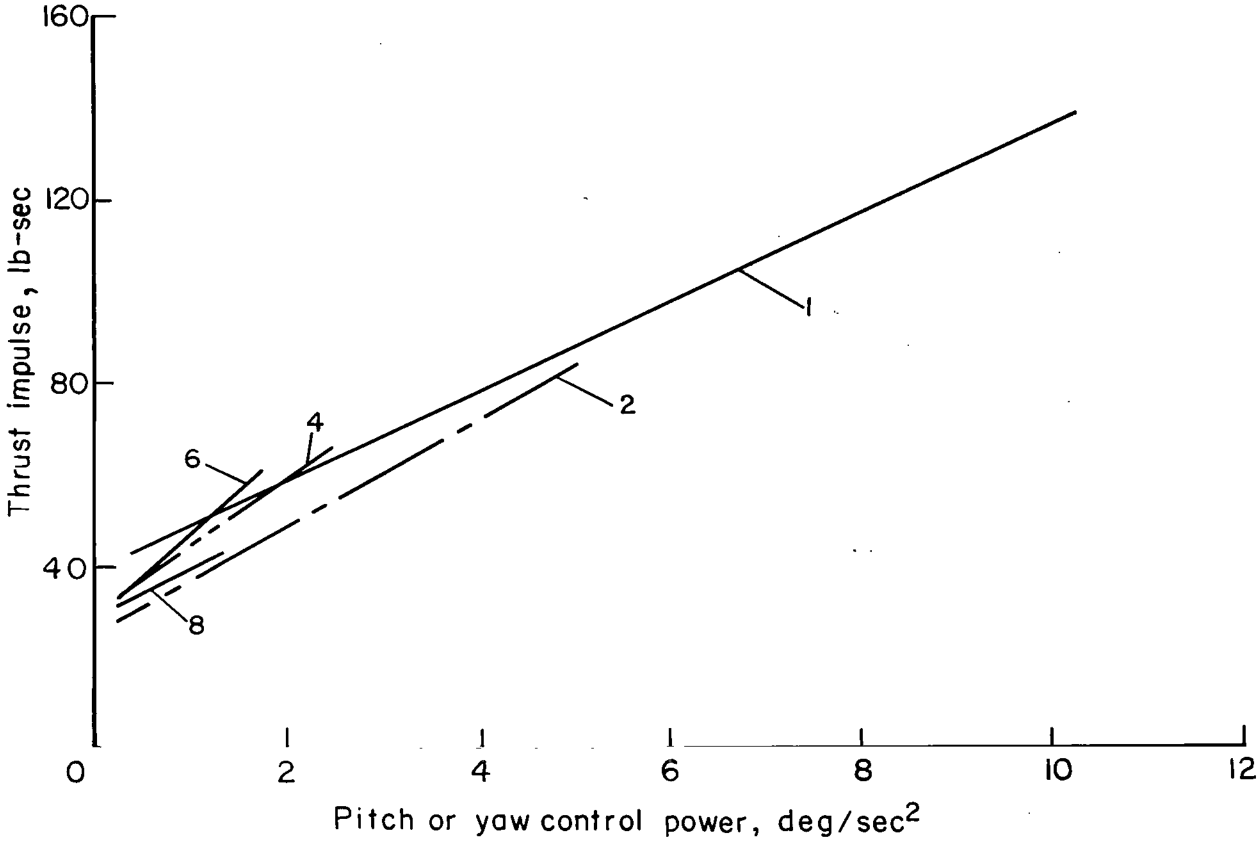
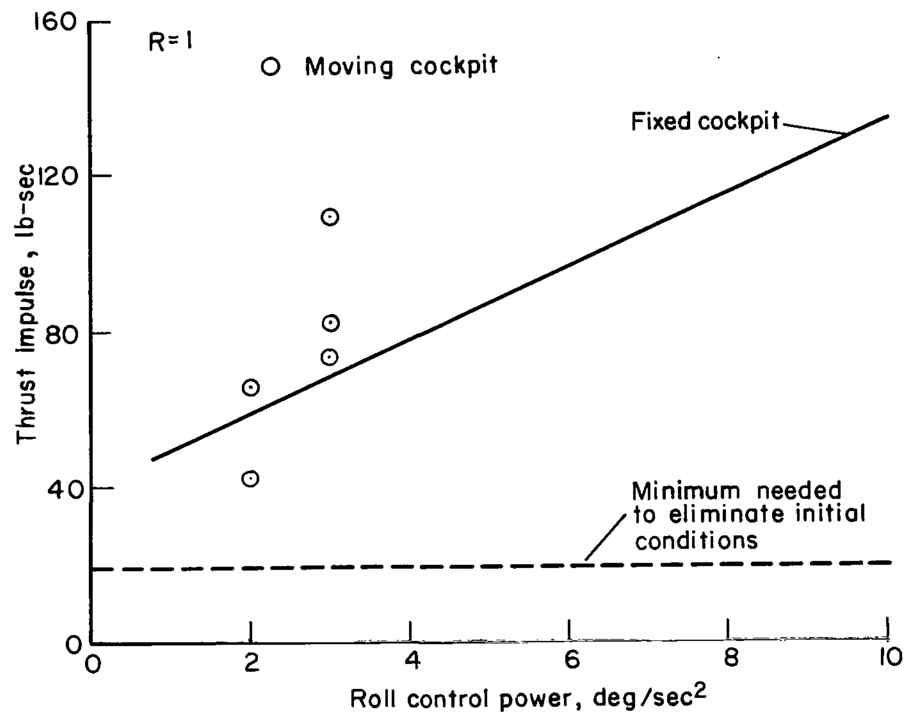
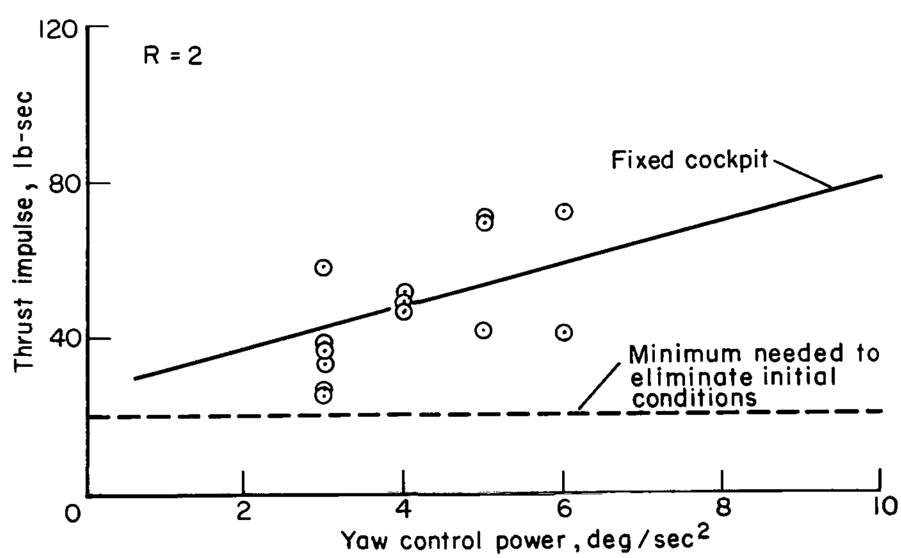


Figure 12.- Variation of total impulse with pitch and yaw control power.

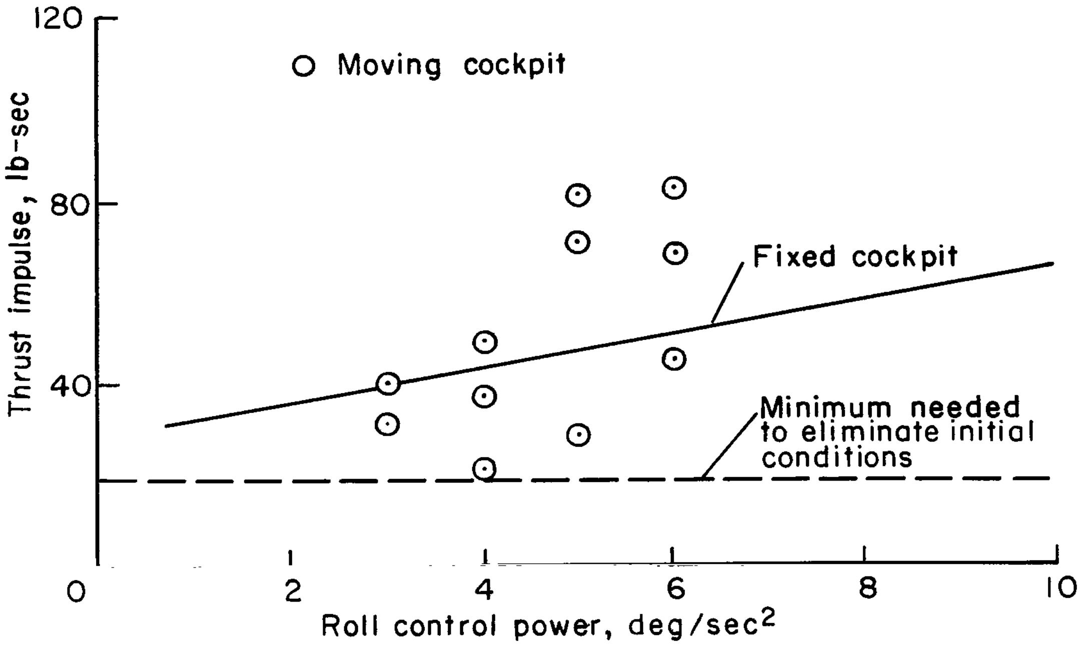


(a) Control power ratio, 1.



(b) Control power ratio, 2.

Figure 13.- Comparison of data for fixed- and moving-cockpit simulators.



(c) Control power ratio, 4.

Figure 13.- Concluded.